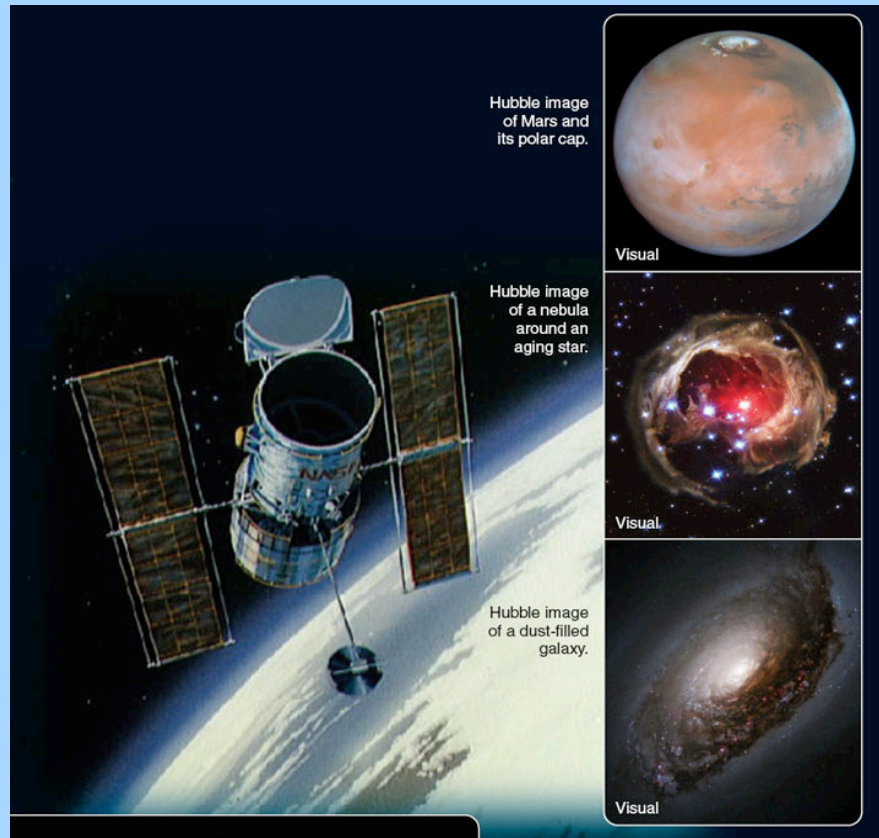
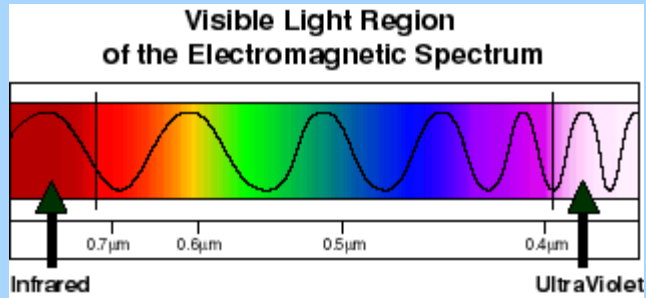


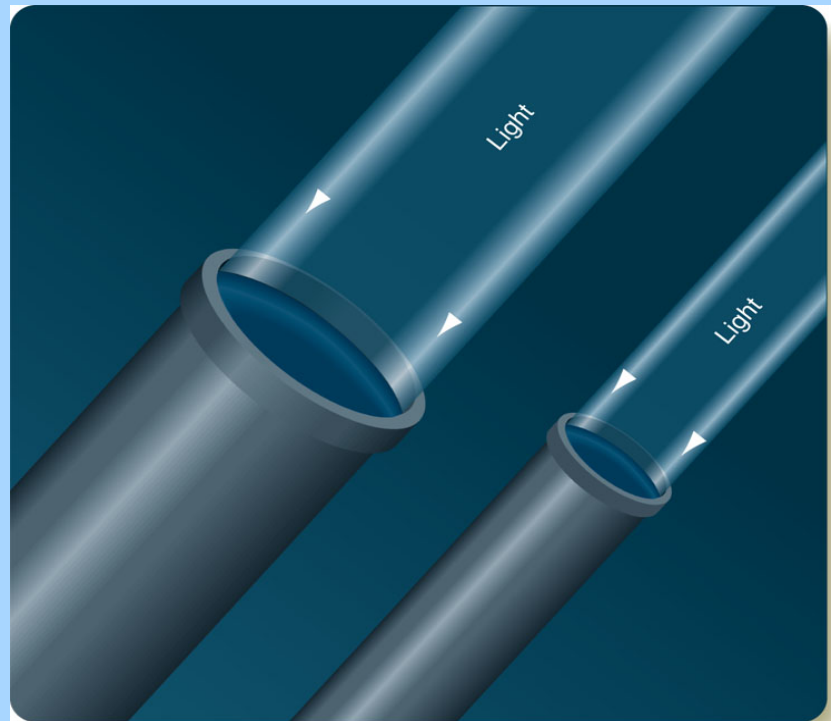
# Light and Telescopes



The key thing to note is that light and matter *interact*. This can happen in four principal ways:

- 1) **emission** – a hot object such as the filament in a light bulb emits visible light
- 2) **absorption** – when you place your hand near a light bulb, your hand absorbs some of the light and heats your hand
- 3) **transmission** – some forms of matter (e.g. air, water) allow light to pass through (where some fraction is also absorbed)
- 4) **reflection/scattering** – light can bounce off metal or glass, or it can bounce in more random directions (such as when it encounters a cloud of dust)

The purpose of a telescope is to gather as much light as possible. All things considered, the most important feature of a telescope is its *diameter*, because that stipulates how much light it can collect.



The area ( $A$ ) of a circle of radius  $r$  is  $\pi r^2$ .

Since the diameter ( $D$ ) of a circle is  $2r$ , the area of a circle is also equal to  $\pi (D/2)^2 = \pi D^2 / 4$ .

The *light gathering power* of a telescope is related to the area of the main light collecting objective (the area of the lens up front or the mirror at the back end). If you have two telescopes of the same design, and one has twice the diameter of the other, the larger telescope has **four** times the light gathering power as the smaller one.

Consider two optical telescopes, one of diameter 10 inches, the other of diameter 40 inches. How much more “light gathering power” does the larger one have?

- A. It depends on the magnification
- B. 4 times as much
- C. 16 times as much
- D. 64 times as much

Consider two optical telescopes, one of diameter 10 inches, the other of diameter 40 inches. If we use the same digital camera on each telescope to take a 60 second exposure, how much fainter are the faintest stars detectable on a dark, moonless night in an image made with the larger telescope?

- A. It depends on the magnification
- B. 4 times fainter
- C. 16 times fainter
- D. 64 times fainter

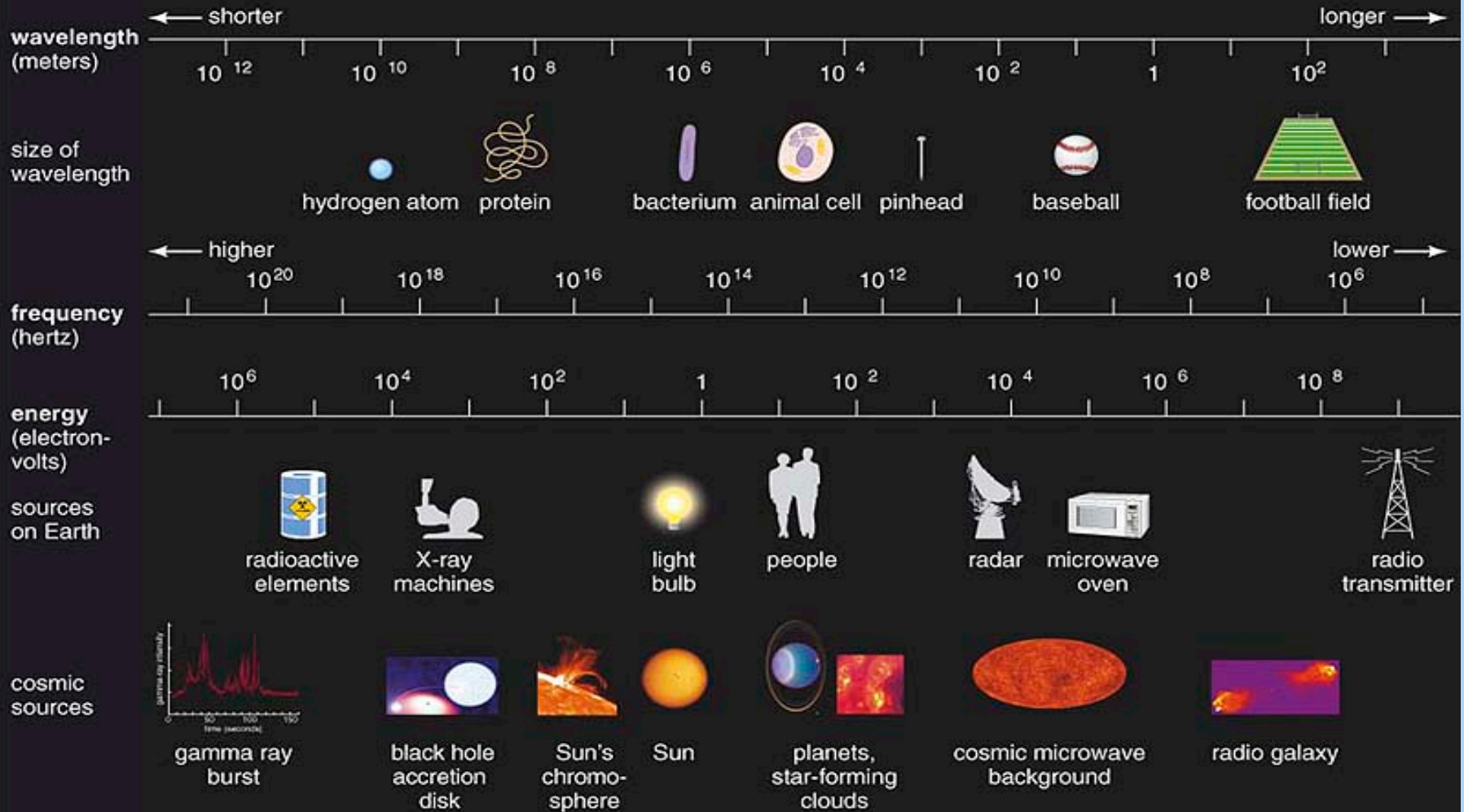
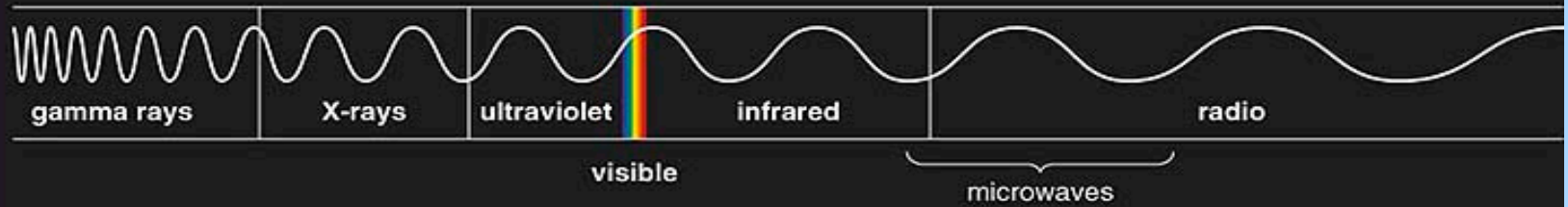
The speed of light *in a vacuum* is a constant (**c**), roughly 300,000 km/sec. Newton spoke of light as a particle, and to a certain extent he was right. But it can also be thought of as waves. A “particle of light” (**photon**) can be considered a bundle of waves.

The relationship between the wavelength ( $\lambda$ ) and frequency (f) of light is:

$$\lambda f = c \quad .$$

Light visible to our eyeballs has wavelengths between 400 and 700 nanometers, or 4000 to 7000 Angstroms.

# The Electromagnetic Spectrum





Reading question:

Which of the following is a kind of light that has the shortest wavelengths and the highest energies?

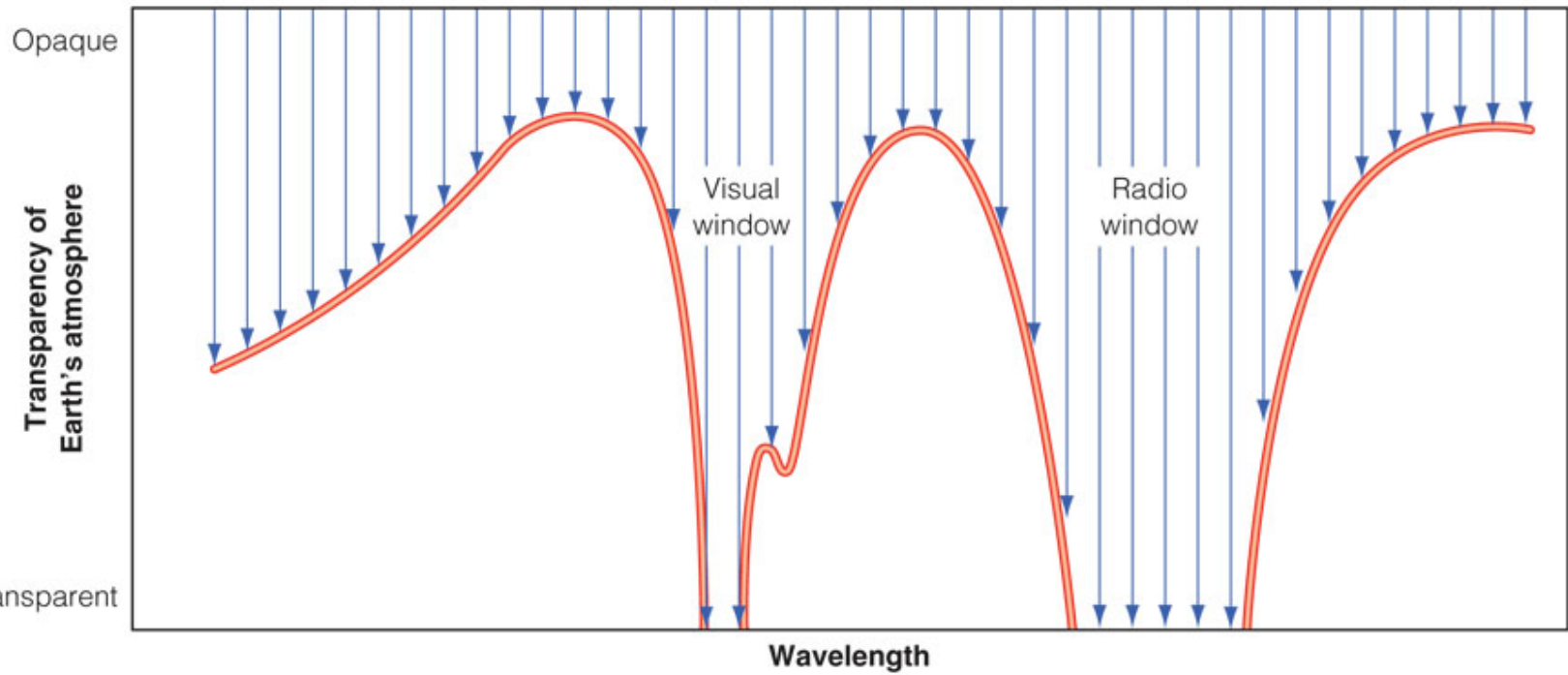
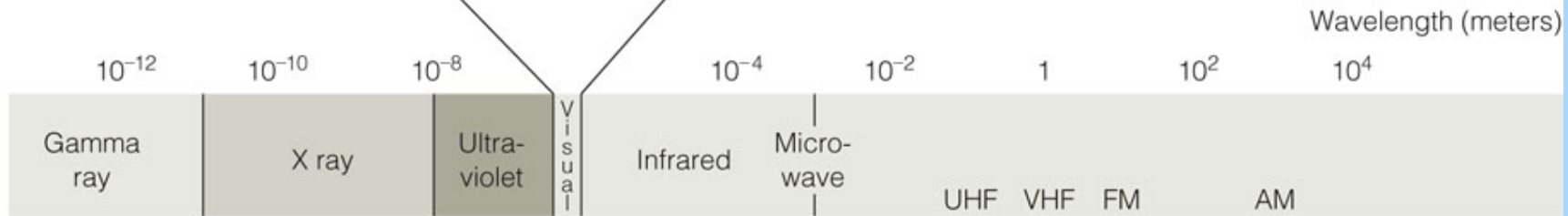
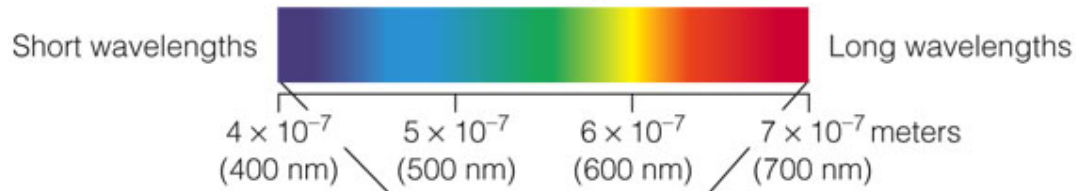
- A. Ultraviolet light
- B. Radio waves
- C. Visual light
- D. Gamma rays
- E. Cosmic rays

Reading question:

Which of the following light waves moves most slowly?

- A. Ultraviolet light
- B. Visible light
- C. Infrared light
- D. Radio waves
- E. They all move at the same speed

### Visible light



Short wavelength light waves have high energies and long wavelength light has low energy. The energy of a photon can be calculated as follows:

$$E = h c / \lambda ,$$

where h is Planck's constant.

High energy photons like UV light, X-rays, and gamma rays can damage your body. Low energy waves like radio waves are not harmful.

object

gives off light at

matter spiralling into  
black hole

X-rays

very hot stars  
Sun-like stars  
planets  
interstellar hydrogen

ultraviolet/optical  
optical/IR  
reflected optical + IR  
radio

The atmosphere blocks X-rays and gamma rays from reaching sea level. Some UV light gets through. Some infrared (IR) light gets through.

High altitude observatories like Mauna Kea are good sites for optical and IR astronomy because they are halfway to space. Half of the Earth's atmosphere is below you.



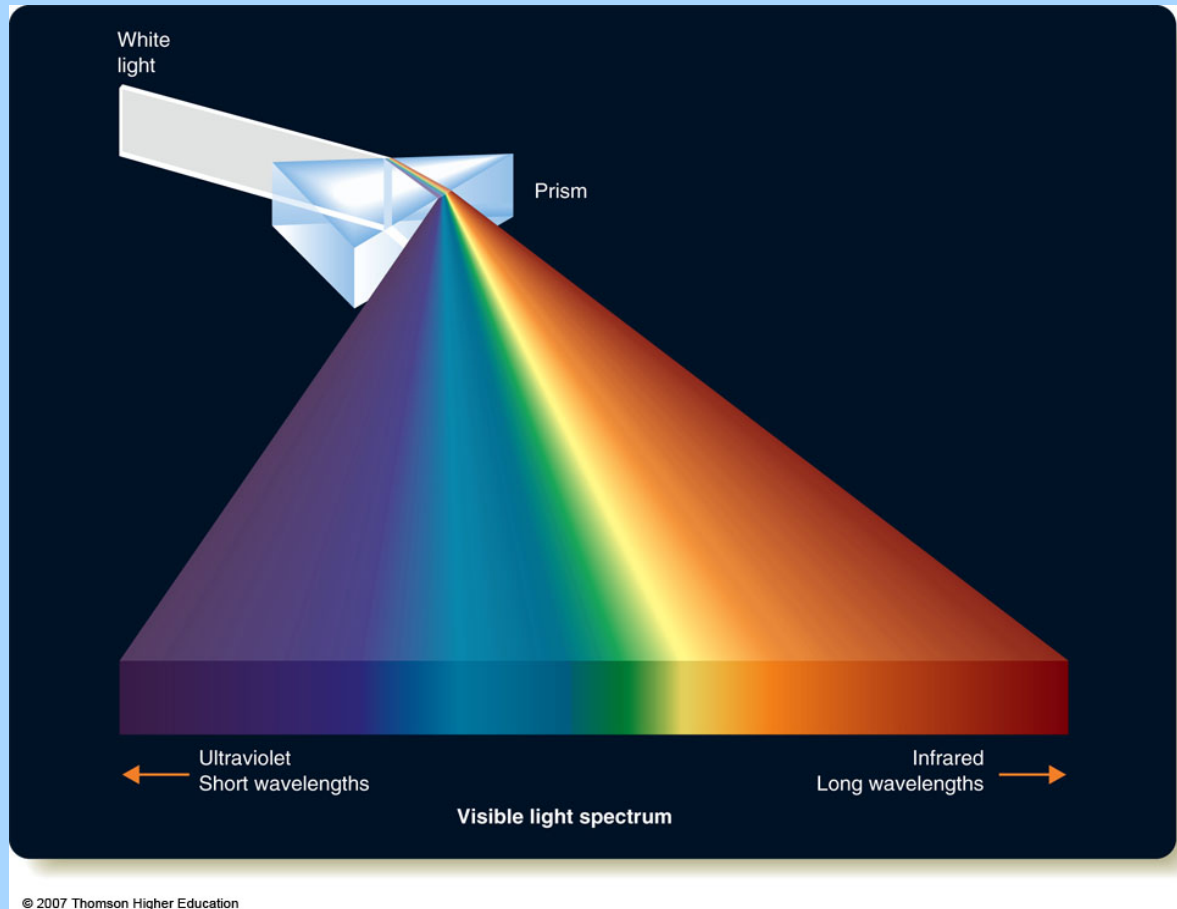
## Two kinds of Telescopes

**refractor** – primary light gathering element is a  
*convex lens*

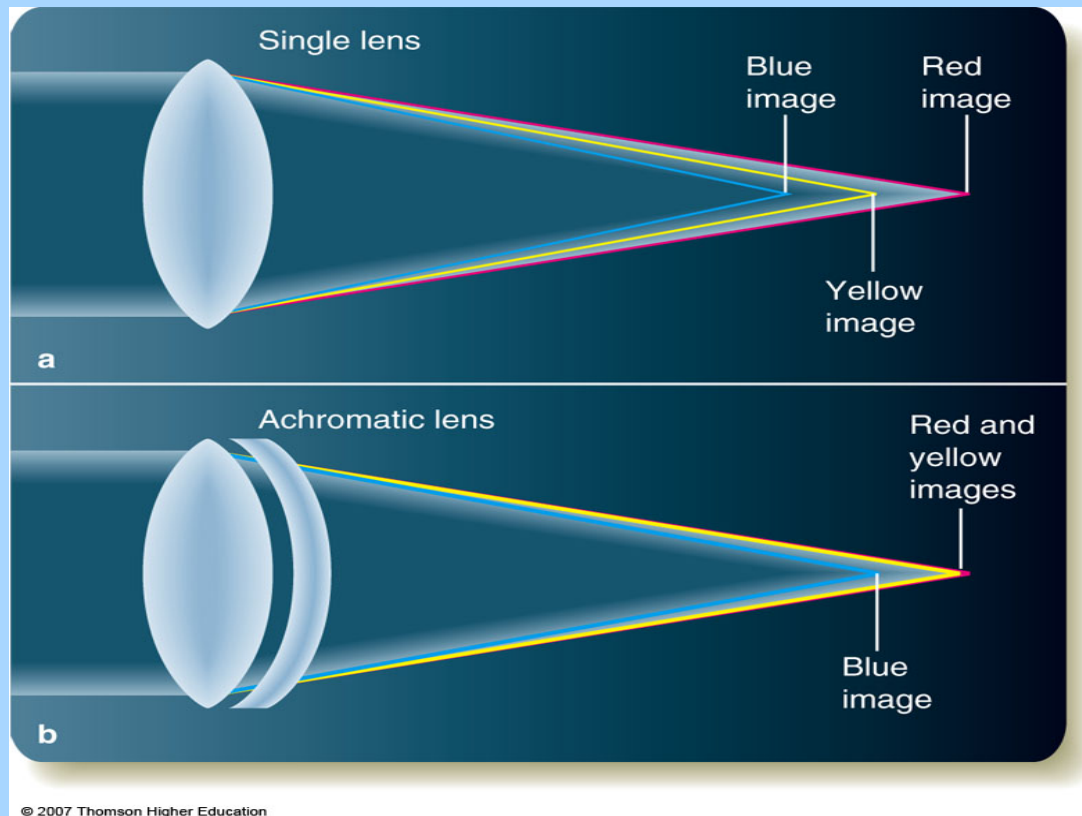
**reflector** – primary light gathering element is a  
*concave mirror*



Blue light is refracted more than red light

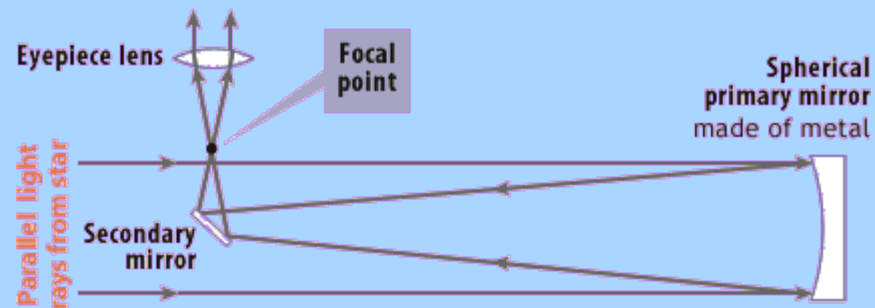


As a result, Galileo's refractors suffered from a bad optical feature. He could not bring all the colors to focus at the same place.



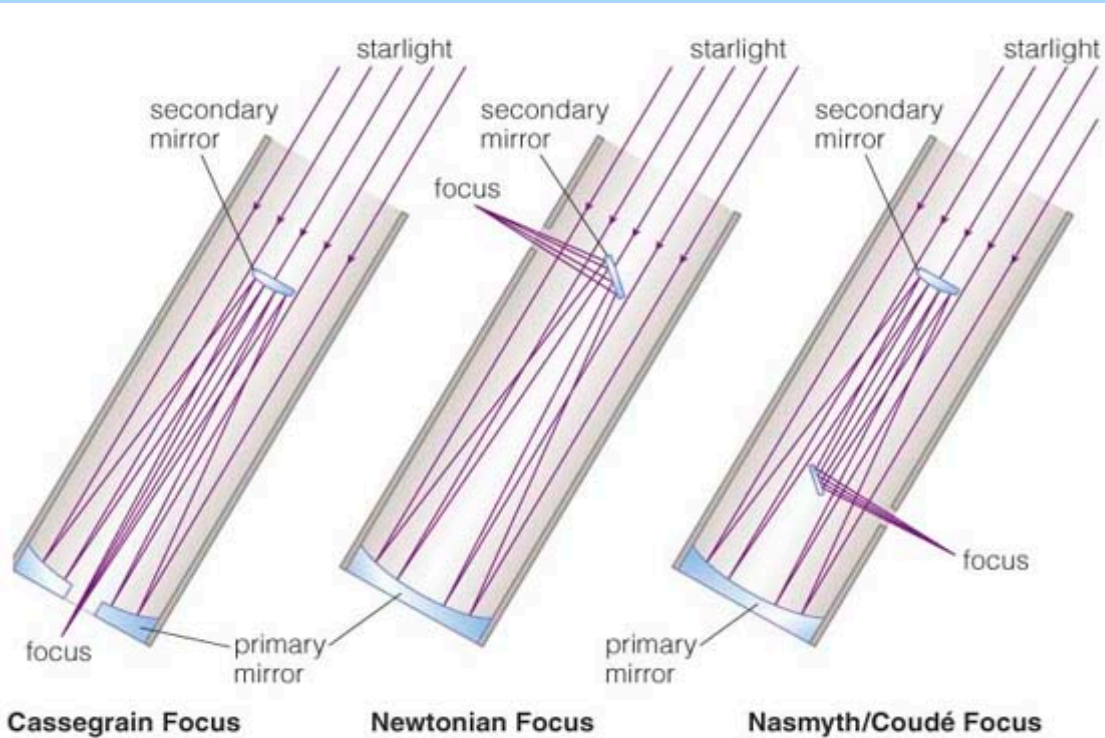
Refractors suffer from *chromatic aberration*.

Newton constructed the first reflecting telescope in 1668. It consisted of a concave primary mirror, a flat secondary mirror, and an eyepiece at the side.





The world's largest refracting telescope is at Yerkes Observatory in Williams Bay, Wisconsin

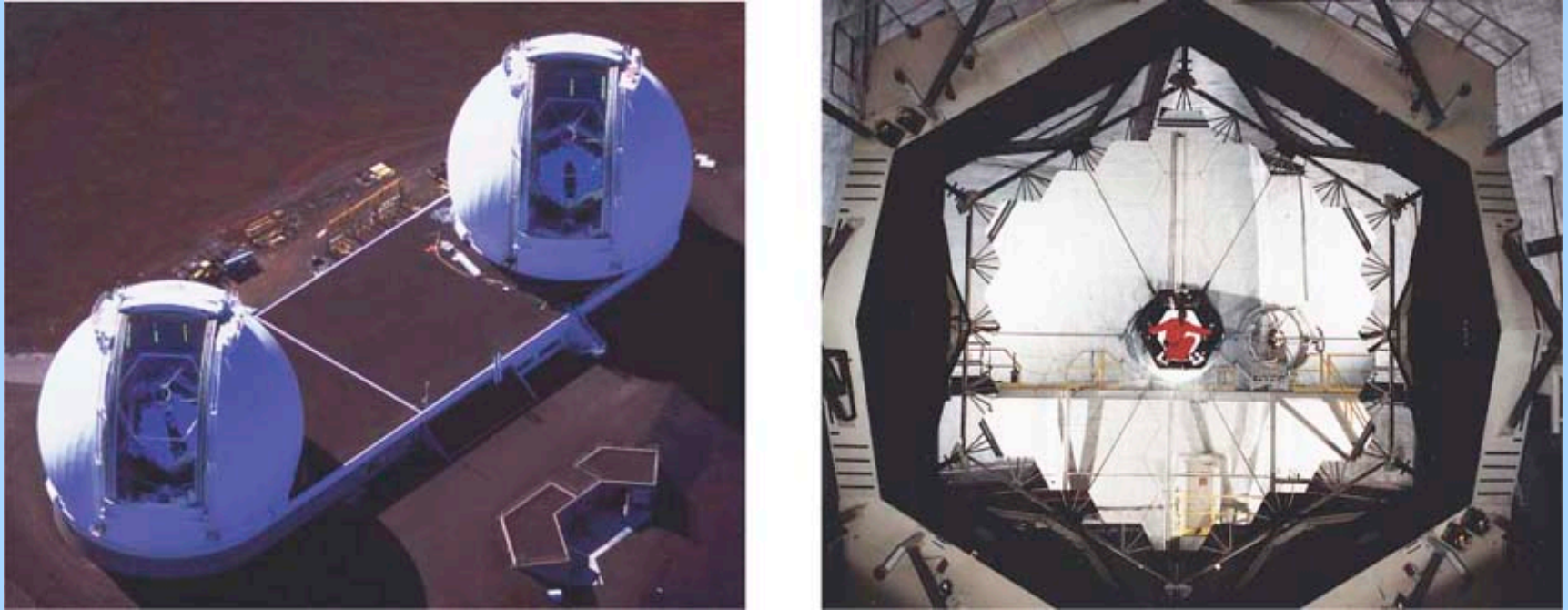


**a** Three variations on the basic design of a reflecting telescope. In all cases, a reflecting telescope collects light with a precisely curved primary mirror that reflects light back upward to the secondary mirror. In the *Cassegrain* design, the secondary mirror reflects the light through a hole in the primary mirror, so that the light can be observed with cameras or instruments beneath the telescope. In the *Newtonian* design, the secondary mirror reflects the light out to the side of the telescope. In the *Nasmyth* and *Coudé* designs, a third mirror is used to reflect light out the side but lower down than in the *Newtonian* design.



**b** The Gemini North telescope, located on the summit of Mauna Kea, Hawaii, is a reflecting telescope with the *Cassegrain* design. The primary mirror, visible at the bottom of the large lattice tube, is 8 meters in diameter. The secondary mirror, located in the smaller central lattice, reflects light back down through the hole visible in the center of the primary mirror.

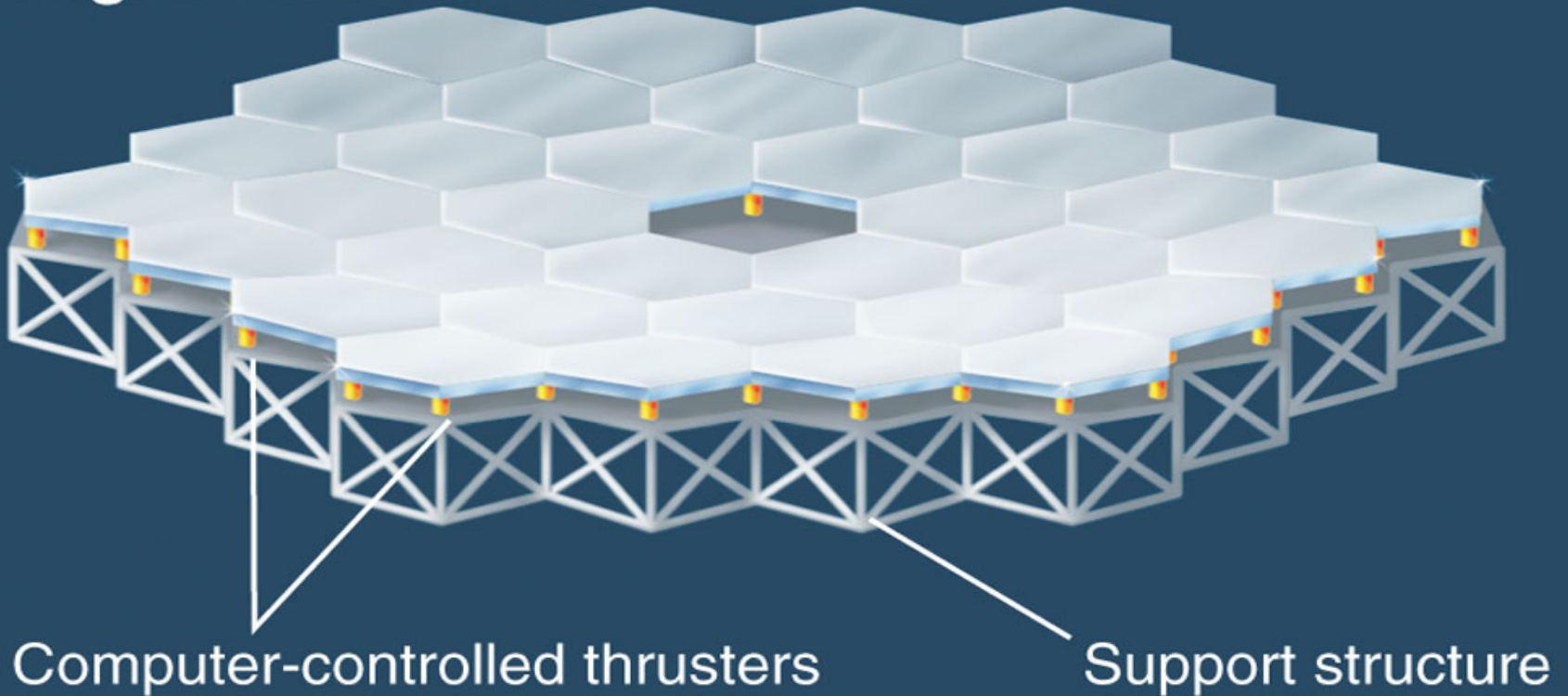
## 3 kinds of reflecting telescopes



Each of the 10-m Keck telescopes at Mauna Kea, Hawaii, has a primary mirror consisting of 36 hexagonal segments. Signals from the two telescopes have been combined, simulating a much larger telescope.

In order to make a telescope larger than 8-m in diameter, it is necessary to have a segmented primary mirror, or combine the light of several mirrors into one telescope.

## Segmented mirror



The **magnification** of a telescope is simply the focal length of the primary lens/mirror divided by the focal length of the eyepiece:

$$M = F_o / F_e .$$

So – any telescope can get any magnification! You just need a very short focal length eyepiece to get 1000 X. However, you are limited by the atmosphere and the quality of your optics. For a 6-inch diameter telescope, the effective maximum magnification is about 150 X.



At 8:31 CDT on Tuesday morning, September 22, 2020, It became autumn in the northern hemisphere and summer in the southern hemisphere. At that moment what was the declination of the Sun?

- a)  $+23 \frac{1}{2}$  degrees
- b) 0 degrees
- c)  $-23 \frac{1}{2}$  degrees
- d) It depends on your latitude.

One way to describe a telescope is by specifying its diameter and its focal ratio (the ratio of the focal length divided by the diameter). Thus, a 4 ¼-inch f/4 reflector has a focal length of 17 inches, or 432 mm.

If we have such a telescope and we have eyepieces of focal length 25 mm, 9 mm, and 6.4 mm, what is the maximum magnification you can achieve with this equipment?

- a) 17 X
- b) 27 X
- c) 48 X
- d) 67 X

## Review slide

How much light a telescope can gather depends on the *area* of the primary light gathering element. Since area is proportional to the square of the diameter, two telescopes of different diameters will have **light gathering power** that scales with  $D^2$ .

$$\text{LGP}_A / \text{LGP}_B = (D_A / D_B)^2$$

Thus, for two telescopes of comparable optical quality at the same location, if one has twice the diameter of the other, it detects 4 times as many photons, so can detect fainter stars.

Question from supplementary reading:

What do we mean by the term “quantum efficiency”?

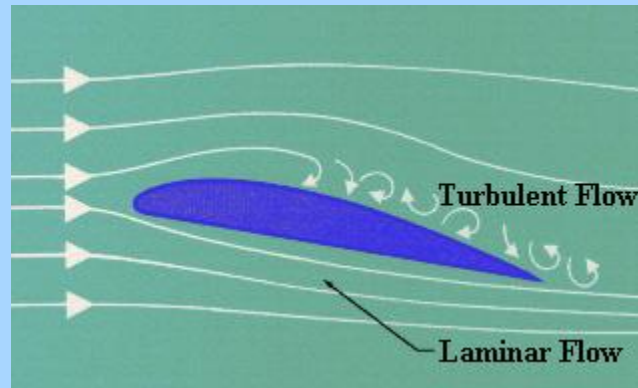
- a. The effectiveness of the evil organization Quantum in the James Bond movie Quantum of Solace
- b. The ability of light to move through air
- c. The ability of light to move through water
- d. The percentage of photons hitting a light sensitive element that is converted by chemical action (film) or converted into electrons which we can count

A cooled Charge Coupled Device can achieve what peak quantum efficiency?

- a. 0.8 percent
- b. 8 percent
- c. 80 percent
- d. 180 percent

The twinkling of bright stars is caused by

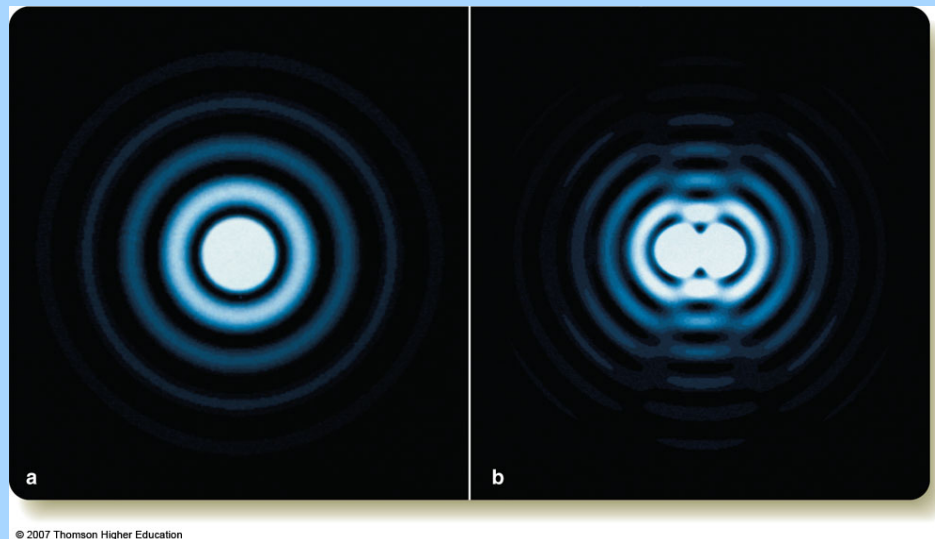
- a. inherent variability of the stars themselves
- b. passing clouds
- c. turbulence in the atmosphere and refraction of light through it
- d. it's a psychological effect



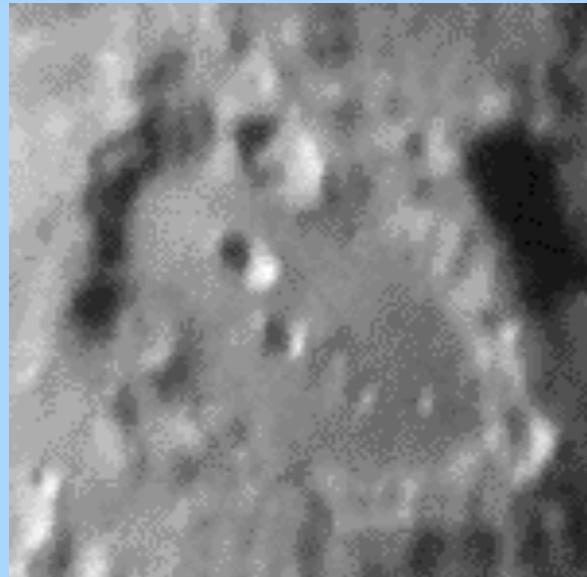
Most mountain observatories are built within 50 miles of the ocean, because it is found that there is smooth, laminar flow of air. High in the Rocky Mountains, however, the air is more turbulent.

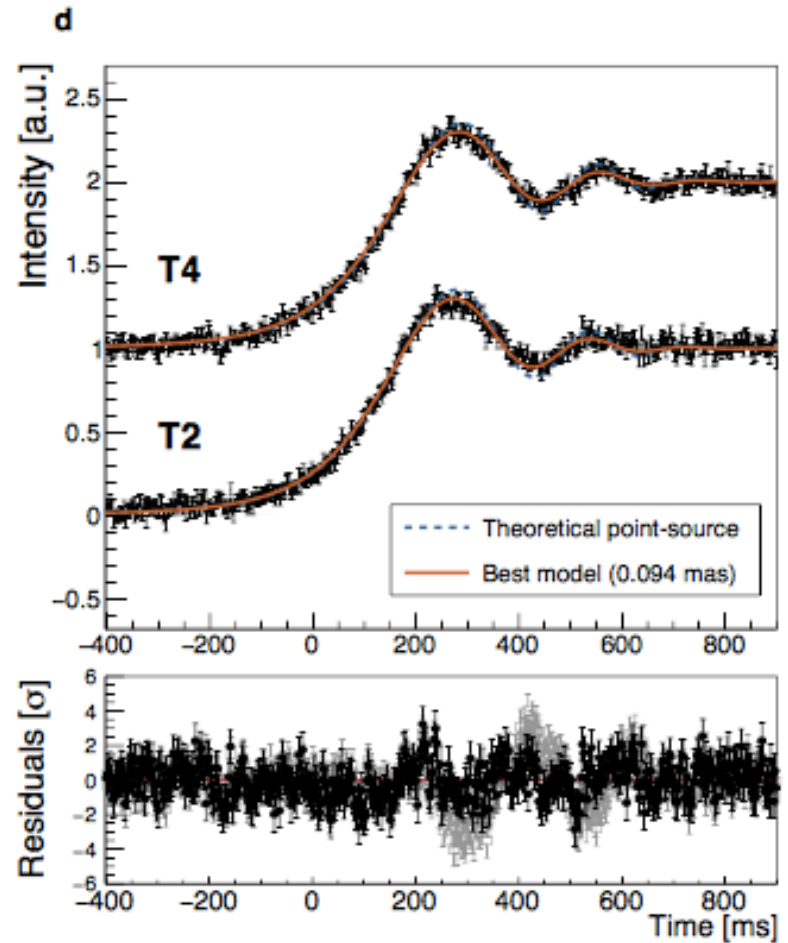
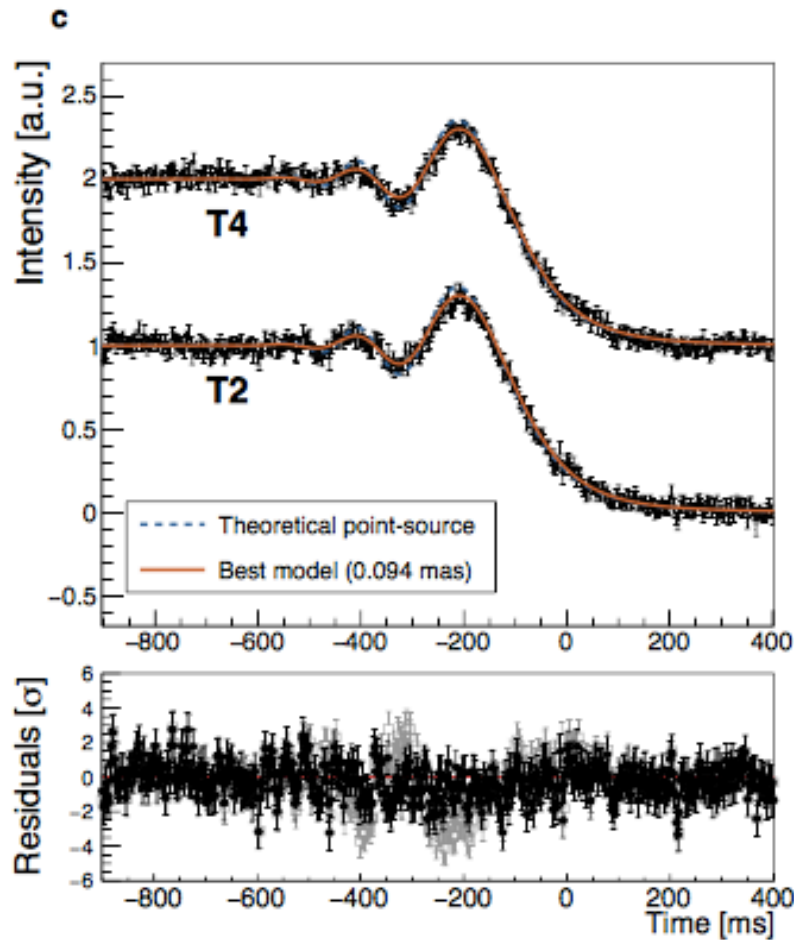
If a site gives very sharp stellar images, it is said to have good **seeing**. At Cerro Tololo, Chile, the typical seeing is about 1 arc second. At Mauna Kea, Hawaii, the typical seeing is 0.6 arcsec.

Still, a telescope has a theoretical limit for being able to resolve detail in astronomical images. This is because of a property of waves called **diffraction**.









Diffraction of starlight at start and end of occultations of stars by asteroids. (arXiv: 1904.06324)

At optical wavelengths (550 nm = 5500 Angstroms), the **resolving power** of a telescope in arc seconds is related to the diameter of the telescope in cm as follows:

$$\alpha = 13.8 / D$$

Thus, for a 25 cm diameter telescope, the theoretical resolving power is 0.55 arcsec. That assumes that the effects of the atmosphere can be completely eliminated.

A practical example: what size telescope do you need to read a license plate from an orbiting satellite?



If a letter is 6 cm in size and the satellite is 200 km away, a letter subtends an angle of 0.062 arcsec. You need a 2.2-m telescope with *adaptive optics* to have a chance. That is the size of the Hubble Space Telescope and various spy satellites.

If an object 6 cm in size is viewed at a distance of 200 km, what angle does it subtend?

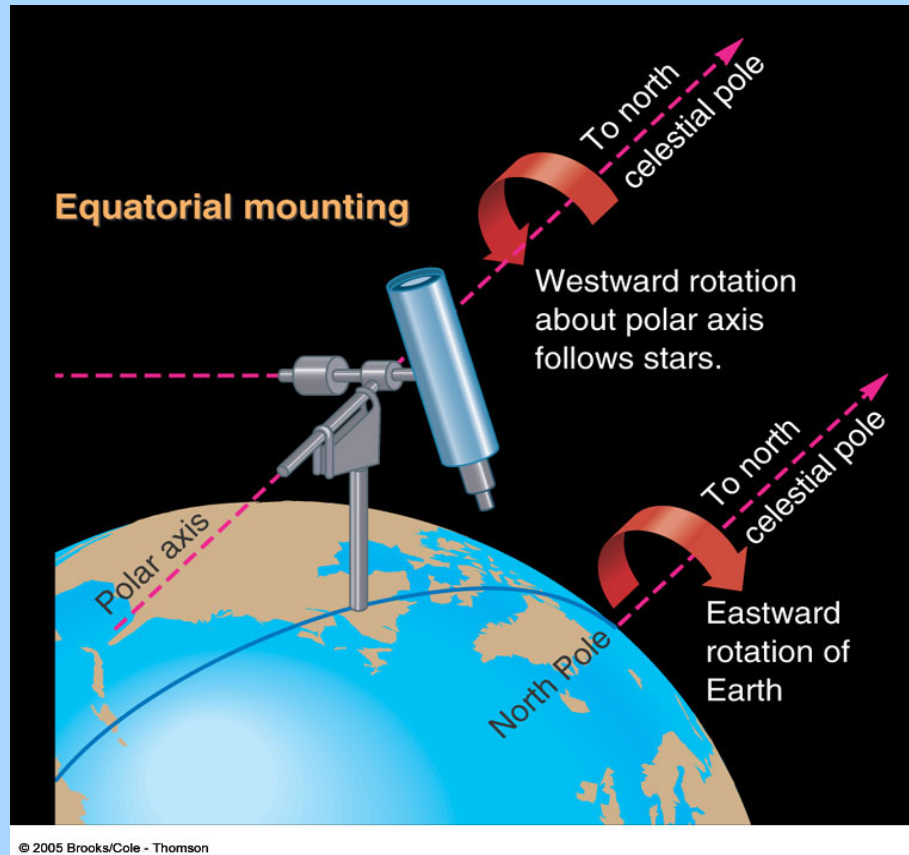
$$\alpha_{\text{rad}} = 6 \text{ cm} / (200 \text{ km} \times 10^5 \text{ cm/km}) = 3.000 \times 10^{-7} \text{ rad}$$

$$\begin{aligned} \alpha \text{ (arcsec)} &= 3.000 \times 10^{-7} \text{ rad} \times 206265 \text{ arcsec/rad} \\ &= 0.062 \text{ arcsec} \end{aligned}$$

How big a telescope is needed for this resolution if observing at 550 nm?

$$D_{\text{nm}} = 1.22 \times 550 \text{ nm} / 3.000 \times 10^{-7} \text{ rad} = 2.24 \times 10^9 \text{ nm}$$

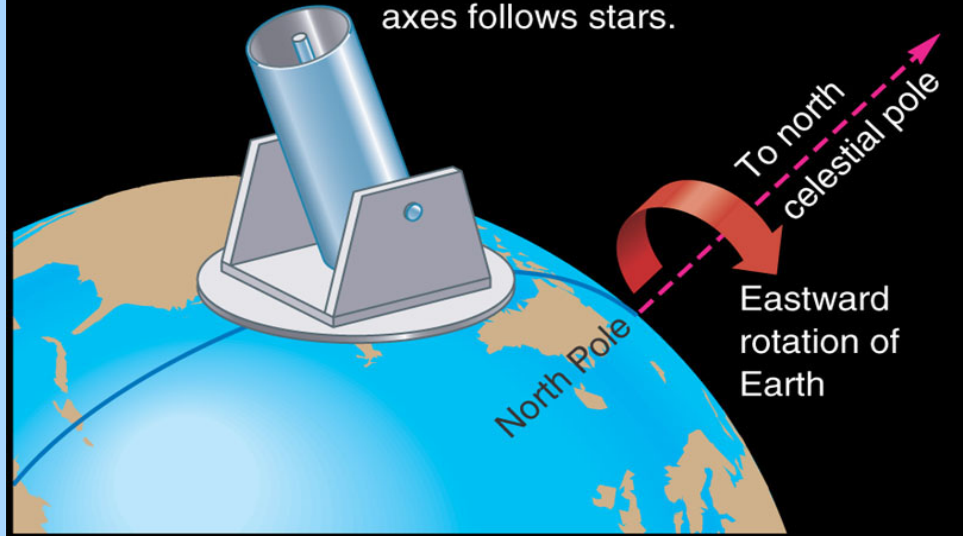
divided by  $10^9 \text{ nm} / \text{meter}$  → 2.24 meters.



An equatorial mounting can be aligned on the celestial pole, and the clock drive can turn the telescope at 15 degrees per hour to track on the stars.

## Alt-azimuth mounting

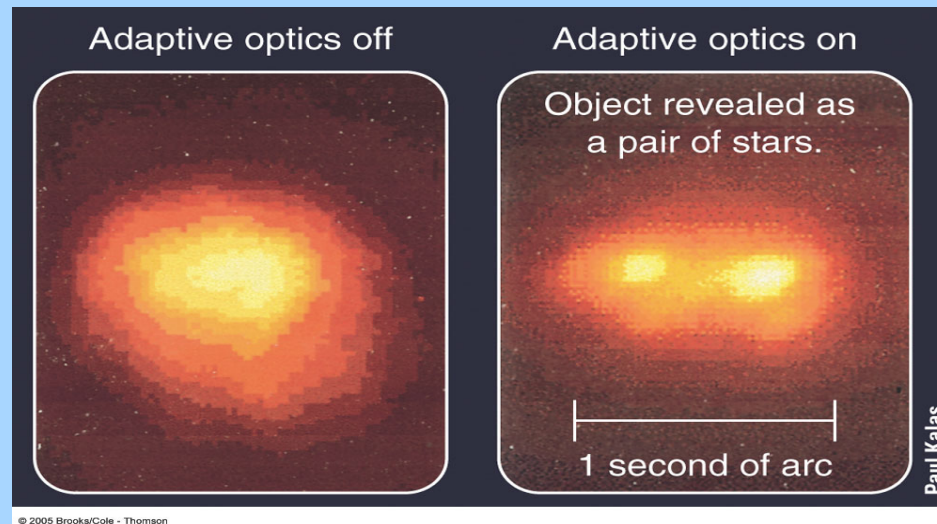
Computer control of motion about both axes follows stars.



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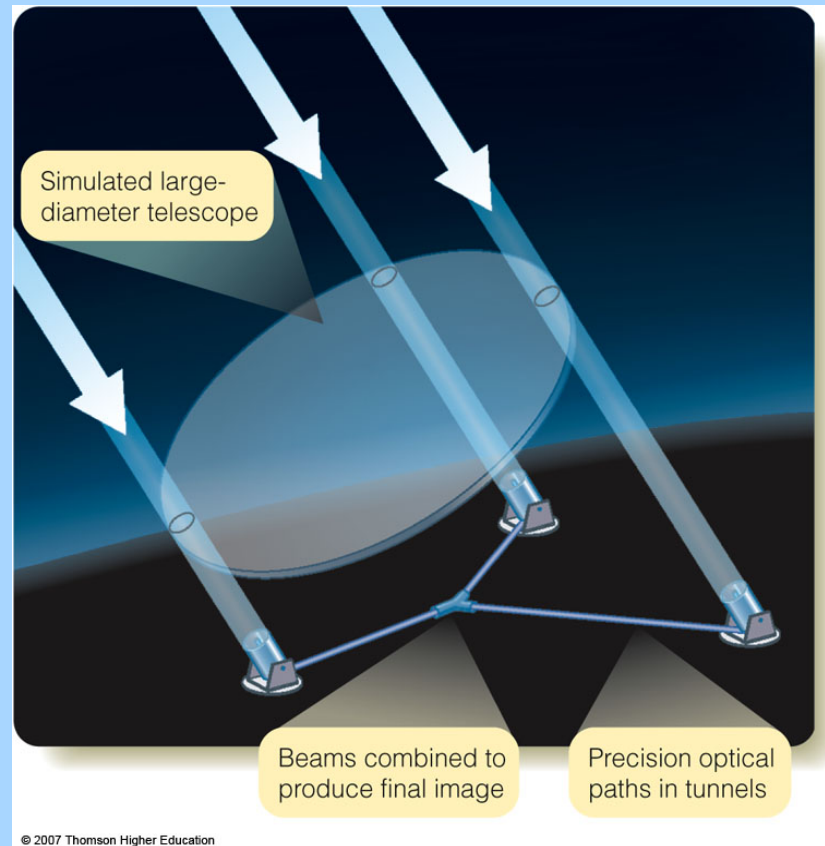
This kind of telescope mounting requires computer control, as both altitude and azimuth change continuously. But all large modern scopes have such mountings.

Computer controlled mirrors have been designed which can counteract the turbulence in the Earth's atmosphere and give resolution close to the theoretical limits.





Thanks to the wave nature of light, it is possible to simulate a large telescope by combining the signals from multiple dishes.





Such a telescope array does not have the *light gathering power* of a full size telescope of the same diameter. But it does have the same *resolving power*.

The resolving power of a telescope is actually a function of the size of the telescope and the wavelength of light:

$$\alpha = 1.22 \lambda / D \quad ,$$

where  $\alpha$  is measured in radians and  $\lambda$  and  $D$  are measured in the same units of distance.

Since the wavelength of visible light is roughly half a micron, the mirror must be ground and polished to the right shape +/- a few percent of a micron, so the mirror must be very rigid.

Radio waves have wavelengths of millimeters to meters, so the radio dishes have to accurate to a tenth of a millimeter to 10 cm. Thus, they can be made of wire mesh and can be built to less exacting standards.

But in order to detect faint radio signals, radio telescopes must be *big*.

If we operate a radio telescope at  $\lambda = 21$  cm, what must its effective diameter  $D$  be so that the resolution is 0.55 arcsec?

Convert to radians

$$\alpha_{\text{rad}} = 0.55 \text{ arcsec} / (206265 \text{ arcsec/rad}) = 2.67 \times 10^{-6} \text{ rad}$$

$$D_{\text{cm}} = 1.22 \lambda / \alpha_{\text{rad}} = 1.22 \times 21 \text{ cm} / 2.67 \times 10^{-6} =$$

$$9.61 \times 10^6 \text{ cm} / (10^5 \text{ cm/km}) = 96.1 \text{ km}$$

Call it 100 km.



b

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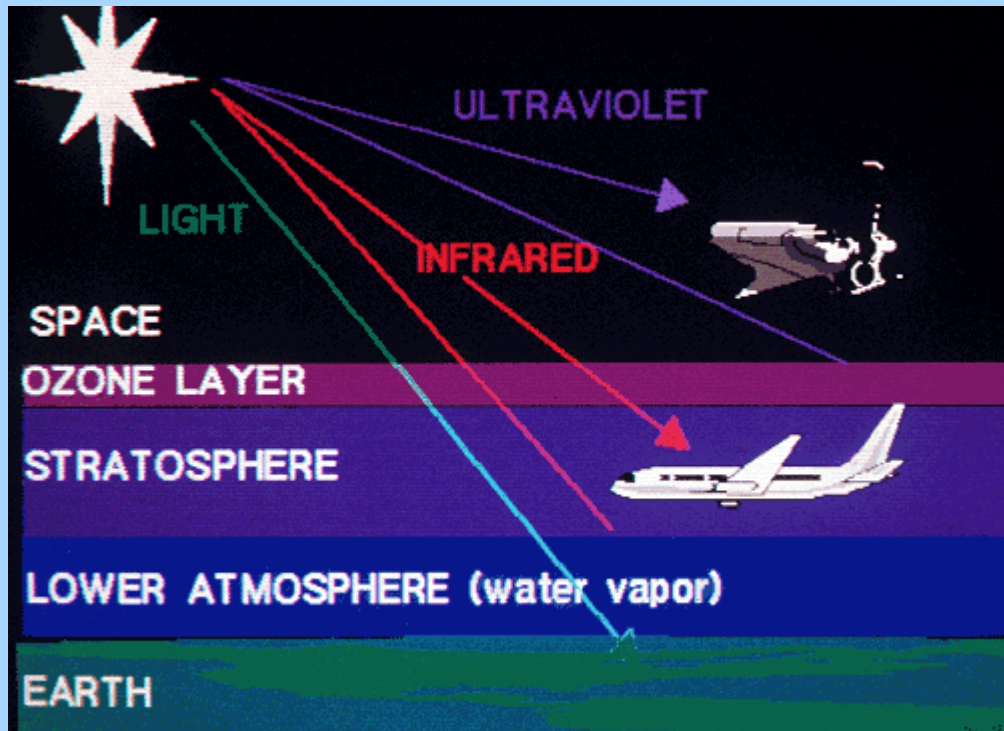
Why do radio telescopes have to be so big?

- a. Radio waves have low energy
- b. Radio waves have long wavelengths
- c. Because of the diffraction limit being a function of wavelength, they have terrible resolution unless they are very large



NASA's Kuiper Airborne Observatory flew a 91-cm telescope to altitudes as high as 45,000 feet. It operated from 1975 to 1995.





The KAO could fly above the tallest mountain on Earth, so could be used for infrared astronomy impossible at ground-based observatories.



Astronomers and crew worked in a pressurized cabin, while the telescope was effectively outside the plane.

X-ray and gamma-ray telescopes must operate outside the Earth's atmosphere.



# Optical and IR telescopes outside the Earth's atmosphere reach their theoretical limits of resolution.

